DESIGN AND MANUFACTURE OF AN ULTRA-LIGHTWEIGHT PROPELLANT MANAGEMENT DEVICE

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ABSTRACT

An ultra-lightweight Propellant Management Device (PMD) was required for an interplanetary mission, and a new PMD development program was conducted to design, fabricate, and test this PMD.

The PMD is designed for installation into a customer-supplied tank shell. There are several unusual features about this PMD: (1) it contains both pressurant inlet and propellant outlet ports, (2) the PMD is installed into a threaded outlet boss, (3) the weight of the PMD must be no more than 0.1 kg (0.22 lbm), and (4) the PMD is designed for horizontal ground operations and launch.

PMD performance analysis was conducted to design this PMD, and PMD structural analysis was performed to validate the PMD design. This PMD was made from all-titanium components, including porous screens. Only existing processes and procedures were used during the fabrication process. The PMD was bubble point tested prior to delivery. All PMDs have been delivered to the customer.

INTRODUCTION

In 2000 Pressure Systems, Inc. (PSI) was contracted to design and fabricate an ultra-lightweight PMD for an interplanetary mission. This PMD must be capable of horizontal ground filling, ground draining, ground handling, and launch. The PMD must contain both the pressurant inlet port and the propellant outlet port. Additionally, the PMD was designed for quick installation into a customer-furnished propellant tank shell via a threaded boss. Above all, this PMD must be lightweight, weighing no more than 0.1 kg (0.22 lbm). A sketch of this PMD is presented below in Figure 1.

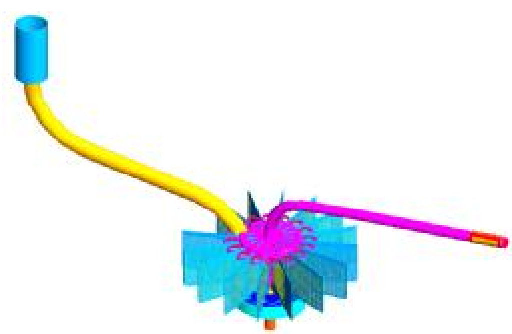

Figure 1, An ultra-lightweight PMD

PMD DESIGN & ANALYSIS

I. PMD Introduction & Requirements

The ultra-lightweight PMD is a passive surface tension device designed to provide gas free hydrazine during all mission accelerations with a minimum safety factor of two. This PMD is designed for use in a tank with non-hemispherical heads.

As with most PMD's, the lightweight PMD is specifically designed for the intended mission. The mission requirements include horizontal ground operations & initial launch followed by a high spin rate launch phase. On orbit operations are conducted at two distinct lower spin rates.

The tank is positioned in the spacecraft with the propellant outlet outboard. Therefore, the centripetal acceleration resulting from spinning settles liquid over the outlet. However, the axial acceleration during launch and on orbit operations is lateral relative to tank.

The mission requirements are summarized in Table 1.

Four requirements are unusual for this PMD: (1) both the pressurant inlet and propellant outlet are located in the same end of the tank, (2) the titanium PMD must be installed in a customer-supplied head via a threaded outlet boss, (3) the maximum allowable PMD mass is 0.1 kg (0.22 lbm), and (4) the PMD must allow horizontal ground filling, ground draining, ground handling, and launch.

These unusual requirements dictated a unique PMD.

II. PMD General Design Description

The ultra-lightweight PMD, consisting of a 15-panel sponge and a screen-covered pickup assembly, is illustrated in Figure 2.

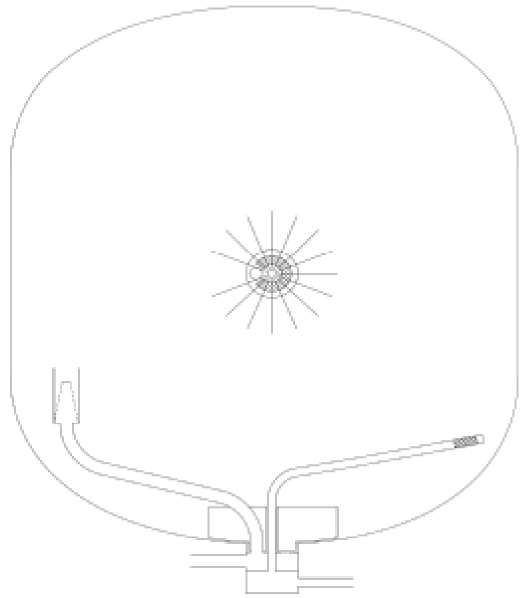

Figure 2: General PMD Configuration

The PMD is screwed into the propellant head outlet with the PMD to tank shell seal created by a cone seal. The seal ensures that the screen bubble point integrity is maintained throughout mission. The entire PMD is cantilevered from the outlet boss.

The key PMD components include:

1). A screen covered pickup assembly
2). A radial paneled sponge

<u>The Pickup Assembly</u>. The pickup assembly consists of a screen located in the outlet cap underneath the sponge, and a ground drain tube which extends from the outlet cap to tank sidewall.

Table 1

Propellant Management Device

Performance Requirements Summary

Ground Operations

- Tanks are filled, handled, and drained in the horizontal orientation. Tank outlet is outboard in the spacecraft.
- Fill and drain flow rates may be controlled to:

  a) limit gas trapped in the PMD,

  b) limit structural loading, and

  c) minimize ground drain residuals.
- Tank fill fraction is 67% nominally, 50% minimum, and 73% maximum.

Boost Operations

- Tanks are launched in the horizontal orientation.
- Upper Stage operations require:
  - Spin up to 80 rpm
  - 7.5 g axial acceleration
  - Spin down to 12±4 rpm
- Propulsion system activation occurs at 12±4 rpm. System priming is the first use of propellant with 30.5 in^3 required. The propellant flow rate is limited by an orifice diameter between 0.050 and 0.072 inches.
- Separation produces a 60 msec, 4.5 g axial acceleration followed by 10 sec of coast.
- Spin down is the next major use of propellant. The spin rate at the end of spin down is 2±0.2 rpm. 2±0.2 rpm is maintained throughout the mission.

Orbital Operations

- All orbital operations are conducted at 2±0.2 rpm. The spin rate settles propellant over the tank outlet since the tanks outlets are positioned outboard in the spacecraft.
- Five types of maneuvers occur throughout mission:
  - Turns
  - Nutation Damping
  - Axial firings
  - Lateral firings
  - Pulsing
- Propellant flow rate is 0.3 in^3/s maximum.
- Maximum nutation angle is 17.8 degrees. This lasts for less than 100 seconds.
- Maximum linear acceleration, both axially and laterally, is 0.001 g.
- Angular accelerations were defined for specific cases.
- Operational temperature range is 17-28°C.
- Residual requirement is 0.22 lbm (6.0 in^3). PMD mass and residual mass must be optimized.

The principal on-orbit propellant access point is a screen underneath the sponge. This screen ensures gas free delivery from the sponge during all on-orbit thruster firings. The screen is positioned below the tank inner mold line in the outlet cap. This position ensures minimum on-orbit residuals.

Ground drain tube is included as part of the PMD unit to allow horizontal ground draining. The tube was designed not to inhibit on-orbit propellant access. The ground drain tube passes through the sponge connecting the flow area underneath the principal screen to the tank sidewall. The end of the tube contains a conical screen to prevent gas penetration during on-orbit operations.

During the mission launch phase, the upper stage will be spinning at a high spin rate. A cylindrical trough is positioned around the conical screen to prevent gas from reaching this screen during high g slosh.

The Sponge. The sponge consists of 15 radial panels extending outboard from the tank center line axis. The sponge panels are retained in place with small lightweight retaining rings.

The sponge is positioned over the outlet to retain liquid during on-orbit propellant slosh and during on-orbit axial thruster firings. During on-orbit axial thruster firings, propellant moves away from the sponge. During on-orbit coast, propellant is settled over the sponge; readying it for another maneuver.

The radial panels are perforated to provide both propellant cross flow and a lightweight PMD solution.

This extremely simple and robust PMD provides low-cost, exceptionally low mass, and high reliability. PMD performance will exceed all requirements.

III. PMD Operational Description

This section describes the PMD function during each phase of the spacecraft mission. The operation is separated into its three logical phases: Ground Operations, Boost Operations, and Orbital Operations.

The various phases of mission that the PMD will encounter and how the PMD will affect the propellant are illustrated in Figure 3, The Operational Sequence.

Ground Operations

The ground operations can be divided into three parts: filling, handling, and draining. These are important not only from a flight standpoint but also from a testing standpoint. One must be able to fill a tank in a reasonable amount of time when following a standard procedure. Similarly, handling and ground draining must be accomplished without extensive effort. The operational sequence depicts ground operations.

Filling occurs with the tank in the horizontal orientation. Initially, the tank pressure is near atmospheric to minimize the trapped gas beneath the outlet screen. Any gas trapped beneath the outlet screen will be compressed upon pressurization and is likely to be dissolved into the low-pressure saturated propellant. The propellant flows into the tank through both the outlet screen and the drain tube screen. Access to the pressurant gas is via the gas tube. The filling process is straightforward.

Handling occurs with the tank in the horizontal position. The flow stagnation region produced by the sponge and screen bubble point should prevent gas from entering the outlet cap. However, the PMD has been designed to ensure that any gas ingested is burped once on orbit.

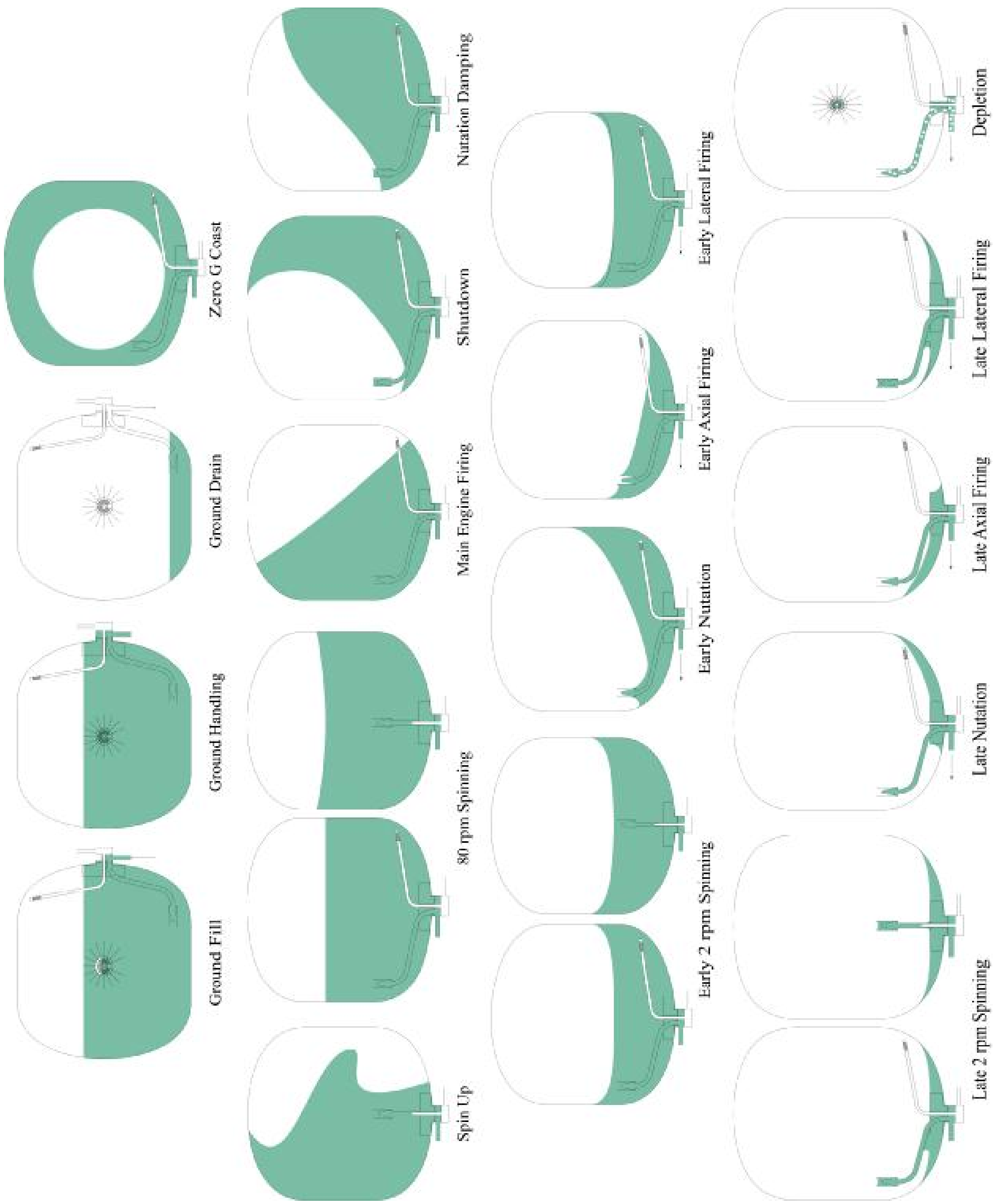

Figure 3: The Operational Sequence

Propellant ground draining may have to be accomplished with the tank in the horizontal orientation. The ground drain tube is positioned to ensure adequate ground draining when horizontal. During ground draining, the outlet screen prevents gas from entering the outlet via the screen bubble point. Ground draining is illustrated in the operational sequence.

Boost Operations

Boost operations can be divided into two phases: 3 axis stabilized launch, and high spin rate upper stage firing. The PMD has been designed to withstand the structural loads during these stages of boost.

The PMD is designed to accommodate horizontal launch. The propellant position and issues are similar to ground handling as illustrated in the operational sequence.

Subsequent to 3 axis stabilized launch, the upper stage is separated and enters zero g coast. During zero g coast the gas bubble in the tank is spherical as illustrated in the operational sequence.

The next mission event is a rapid spin up to 80 rpm. During spin up, the propellant reorients rapidly with the geyser forming in response to the tangential acceleration. A rapid propellant reorientation causes structural loads on the PMD. The PMD has been designed to withstand these loads. The geyser is illustrated in the operational sequence.

During 80 rpm spinning, the propellant is settled over the outlet and the propellant surface is cylindrical. While spinning at 80 rpm, the upper stage solid rocket motor is fired, producing a large lateral acceleration. The propellant will reorient so that the propellant surface is a paraboloid. Both the outlet screen and the drain window screen are submerged during 80 rpm spinning and during main engine firing as illustrated in the operational sequence.

During main engine shutdown, the propellant reorients back into the simply-spinning configuration. During the reorientation, the end of the drain window will be exposed to gas. The duration of the exposure is very short due to the high slosh frequency. The cylindrical trough has been designed to prevent gas exposure of the screen during upper stage shutdown. The trough is full of propellant throughout shutdown as illustrated in the operational sequence.

Nutation may occur during spinning. This may cause propellant slosh that could expose the end of the drain tube to gas. Again the trough will prevent gas exposure of the screen during nutation induced slosh as shown in the operational sequence.

Orbital Operations

After boost, the vehicle is spun down to 12 rpm and the propulsion system activated. The vehicle is then spun down to 2 rpm for all orbital operations. During 2 rpm spinning, the propellant is settled over the outlet and the surface tension forces are significant as illustrated in the operational sequence.

Early in mission, the large amount of propellant in the tank makes propellant access easy. Propellant is required during nutation damping, during axial steady firing, and during pulsed lateral firing.

During nutation damping, slosh in the tank can occur. The PMD is designed to ensure liquid remains in sponge, over the outlet for gas free delivery.

During axial steady firings, the propellant reorients slightly off the tank outlet as illustrated. Again the PMD is designed to ensure liquid remains in the sponge, over the outlet for gas free delivery.

During pulsed lateral firings, the “settling” acceleration is varied and the propellant motion is small. Gas free propellant access is straightforward during pulsed lateral firings.

Late in mission, the small amount of propellant remaining in the tank makes propellant access more difficult. Fortunately, the centripetal acceleration induced by 2 rpm spinning settles propellant over the outlet. The PMD is designed to retain and deliver gas free propellant to depletion.

During nutation damping, the bulk space propellant may move away from the outlet. The sponge has been designed to retain a sufficient amount propellant to ensure gas free delivery during nutation-induced slosh.

During axial steady firings, the propellant pool is oriented away from the outlet. The sponge is designed to reach over into the propellant pool and deliver gas free propellant to depletion.

During pulsed lateral firings, propellant access is straightforward as illustrated in the operational sequence.

The last illustration in the operational sequence is depletion. The PMD is designed to deliver gas free propellant down to the very low residual level of 1.2 in^3 of hydrazine. This exceptionally lightweight PMD also delivered exceptional performance.

IV. PMD Design and Analysis

The principal method of PMD performance verification is analysis coupled with component and tank assembly bubble point and flow loss testing.

The analysis examines, in detail, the fluid's reaction to all phases of mission. The propellant location, reorientation, and flow characteristics are determined and evaluated. The PMD is analyzed to ensure adequate control and delivery of propellant. The porous elements are shown to demonstrate the required margins. In addition, flow losses and flight depletion residual propellant quantities are analytically determined.

Because PMDs have been extensively proven in flight, and drop tower tests have verified the analytical techniques used to design them, no test verification program is required as such testing would yield no new information.

Because each maneuver in the mission can directly affect the PMD, each performance analysis addresses a phase of mission. First, the impact of Ground Operations on the PMD is examined. Second, the impact of and operation during Boost Operations are examined. And finally, the operation of the PMD during all On-Orbit Operations is analyzed.

The specific analyses are listed in Table 2. Due to the summary nature of this paper, no results are presented. The detailed process of PMD design analysis can be found in the series of papers titled *Propellant Management Device Conceptual Design and Analysis: Vanes, Sponges, Traps & Troughs,* or *Galleries* by D.E. Jaekle Jr.[1,2,3,4]

The analyses conducted verified that the PMD will meet all requirements of the specification by providing gas free propellant upon demand.

PMD STRUCTURAL ANALYSIS

A PMD structural analysis was performed to validate the structural integrity of the PMD design. The analysis took into consideration design requirements such as material properties, fluid properties, vibration environment, slosh loads, and design safety factors. The PMD stress analysis concluded with positive margins of safety for all design parameters, as summarized below in Table 3:

Table 2, PMD Performance Analyses

I. General Design Analyses
   A. Pickup Assembly Configuration
   B. Screen Type and Area
   C. Tube Area
   D. Ground Drain Screen Location
   E. Trough Design
   F. Sponge Size & Shape
   G. Sponge Number of Panels

II. Ground Operations
   A. Filling
   B. Handling
   C. Draining

III. Boost Operations
   A. Launch
   B. Upper Stage Operations
   C. System Priming

IV. On-Orbit Operations
   A. Nutation & Turns
   B. Axial Firing
   C. Lateral Firing
   D. Depletion
   E. Flow Losses

Table 3: PMD Safety Margins

Characteristics	M.S.
Pressure tube, yield	+0.15
Pressure tube, ultimate	+0.31
Propellant tube, yield	+0.30
Propellant tube, ultimate	+0.47
Vane, yield	+0.10
Vane, ultimate	+0.05
Tube, crippling	+1.70
Displacement, ultimate	+0.56
Pressurant tube base, yield	+2.20
Pressurant tube base, ultimate	+2.65
Screen, yield	+0.24
Screen, ultimate	+0.36

PMD FABRICATION

The PMD assembly consists of three basic sub-assemblies: the pressurant inlet assembly, the pickup assembly, and the sponge.

Pressurant Inlet Assembly: The pressurant inlet assembly consists of a ¼" tube with a welded screen assembly. One end of the tube is for insertion into the PMD outlet cap. The opposite, pressurant inlet end contains a slot covered by the screen assembly. See Figure 4.

Figure 4, The Pressurant Inlet Assembly

Pickup Assembly: The pickup assembly consists of the 3/8" drain tube assembly and the outlet cap, as shown in Figure 5. The end of the drain tube assembly contains a conical screen within a cup, while the outlet cap is also covered with titanium screen.

Figure 5, The Pickup Assembly

PMD Sponge Assembly: The 15-panel sponge assembly, as shown in Figure 6, is located above the outlet cap. The panels are TIG welded in place.

Figure 6, Sponge Assembly

PMD Assembly: The completed PMD assembly is shown in Figure 7.

Figure 7, PMD Assembly

ACCEPTANCE TESTING

The PMD consists of several sub-assemblies. Each porous element and welded sub-assembly is bubble point tested to ensure a minimum bubble point prior to committing it to the next level assembly. This screening process is designed to eliminate all defective components and sub-assemblies. The completed PMD assembly is also bubble point tested to ensure a minimum bubble point has been achieved.

The PMD acceptance testing is limited to PMD bubble point test, visual examination, and final precision cleaning. The PMD cleaning is only an interim cleaning process, since the completed tank will be cleaned one last time prior to delivery.

CONCLUSION

The PMD design meets all mission requirements. Conservative design and analytical approaches were used during the design of this PMD. It is extremely lightweight, weighing only 0.1 kg (0.22 lbm). It is easy to manufacture - the PMD assembly is fabricated using standard manufacturing processes and procedures, and special materials and processes are not required. It is easy to test, requiring only a bubble point test for final acceptance. Consistent with all PMDs designed and fabricated by PMDT and PSI, this PMD is robust in functionality and simple in manufacturability.

The PMD assembly has successfully concluded final acceptance testing without failure. The production program is complete and all PMD's ordered by the customer have been delivered.

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